Experimental status of deeply bound kaonic states in nuclei

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Abstract. We review recent claims of the existence of deeply bound kaonic states in nuclei. Also we study in details the (K^-, p) reaction on ^{12}C with 1 GeV/c momentum kaon beam, based on which a deep kaon nucleus optical potential was claimed in [1]. In our Monte Carlo simulation of this reaction we include not only the quasi-elastic $K^- p$ scattering, as in [1], but also K^- absorption by one and two nucleons followed by the decay of the hyperon in πN, which can also produce strength in the region of interest. The final state interactions in terms of multiple scattering of the K^-, p and all other primary particles on their way out of the nucleus is also considered. We will show that all these additional mechanisms allow us to explain the observed spectrum with a "standard" shallow kaon nucleus optical potential obtained in chiral models.

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The issue of the kaon interaction in the nucleus has attracted much attention in past years. Although from the study of kaon atoms one knows that the K^--nucleus potential is attractive [2], the discussion centers on how attractive the potential is and whether it can accommodate deeply bound kaon atoms (kaonic nuclei), which could be observed in direct reactions.

All modern potentials based on underlying chiral dynamics of the KN interaction [3, 4, 5, 6, 7] lead to moderate potentials of the order of 60 MeV attraction at normal nuclear density. They also have a large imaginary part making the width of the bound states much larger than the energy separation between the levels, which would rule out the experimental observation of these states.

Deep K^--N optical potentials are preferred by the phenomenological fits to kaon atoms data. One of the most known extreme cases of this type is a highly attractive phenomenological potential with about 600 MeV strength in the center of the nucleus, introduced in [8, 9]. In this picture such an attractive K^-, inserted inside the nucleus, would lead to a shrinkage of the nucleus, generating a new very compact object - kaonic nucleus - with a central density which can be 10 times larger than normal nuclear density. Such super-deep potentials were criticized in [10, 11, 12, 13].

From the experimental side the search for deeply bound K^- states with nucleons is a most direct and clear way to answer whether the K^--nucleon potential is deep or shallow,

because only a deep potential may generate states sufficiently narrow to be observed experimentally. Experimental attempts to resolve this situation have been made since 2004, but the situation is still very unclear.

Several claims of observed deeply bound K^- states have been made. However, the first one, K^-pnn deeply bound state from the experiment at KEK [14], is now withdrawn after a new more precise experiment [15].

Two other claims of the existence of deeply bound kaonic states in nuclei came from the observation by the FINUDA collaboration of some peaks in the (Λp) [16] and (Λd) [17] invariant mass distributions, following the absorption of stopped K- in different nuclei. These were interpreted in terms of deeply bound K^-pp and K^-ppn clusters correspondingly. However, recently it has been shown that these peaks are naturally explained in terms of K^- absorption by two [18, 19, 20] or three [21] nucleons respectively, leaving the rest of the original nuclei as spectator. And for the reactions on heavy nuclei the subsequent interactions of the particles produced in the primary absorption process (Λ, p etc.) with the residual nucleus have to be taken into account [18, 19, 20].

There are also claims of K^-pp and K^-ppn bound states from $\bar{p}$ annihilation in ^4He at rest measured by OBELIX@CERN [22], however their statistical significance is very low. The most recent is the claim of K^-pp bound state, seen in $pp \to K^+X$ reaction, from DISTO experiment [23]. These experimental claims are under investigation now. Before calling in new physics one has to make sure that these data cannot be explained with conventional mechanisms. Also, it is worth mentioning that all above mentioned "experimental claims" are in disagreement with each other.

There is, however, one more experiment where the authors claim the evidence for a strong kaon-nucleons potential, with a depth of the order of 200 MeV [1]. The experiment looks for fast protons emitted from the absorption of in flight kaons by ^{12}C in coincidence with at least one charged particle in the decay counters sandwiching the target. The data analysis in [1] is based on the assumption that the coincidence requirement does not change the shape of the final spectra. We shall see that this assumption doesn't hold and the interpretation of the data requires a more thorough approach than the one used in that work.

One of the shortcomings of Ref. [1] stems from employing the Green's function method [24] to analyze the data. The only mechanism considered in Ref. [1] for the emission of fast protons is the $\bar{K}p \to \bar{K}p$ process, taking into account the optical potential for the slow kaon in the final state. We shall show that there are other mechanisms that contribute to generate fast protons, namely multi-scattering reactions, and kaon absorption by one nucleon, $K^-N \to \pi\Sigma$ or $K^-N \to \pi\Lambda$ or by a pair of nucleons, $\bar{K}NN \to \Sigma N$ and $\bar{K}NN \to \Lambda N$, followed by decay of Σ or Λ into πN. The contributions from these processes were also suggested in Ref. [25].

In the present work, we take into account all the above mentioned reactions by means of a Monte Carlo simulation [26]. As in the experiment [1], we select "good events" with fast protons that emerge within an angle of 4.1 degrees in the nuclear rest frame (lab frame). We plot our obtained $^{12}C(K^-, p)$ spectrum as a function of a binding energy of the kaon, E_B, should the process correspond to the trapping of a kaon in a bound state and emission of the fast proton.

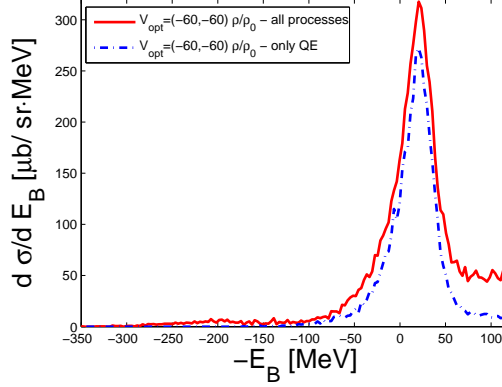We take into account a kaon optical potential $V_{opt} = \mathrm{Re}\,V_{opt} + \mathrm{i}\,\mathrm{Im}\,V_{opt}$, which will

FIGURE 1. Calculated $^{12}C(K^-, p)$ spectra with $V_{opt} = (-60, -60)\rho/\rho_0$ MeV, taking into account only quasi-elastic processes (dash-dotted line), and including all the contributing processes (full line).

influence the kaon propagation through the nucleus, especially when it will acquire a relatively low momentum after a high momentum transfer quasi-elastic collision. In the present study we take the strength of the potential as predicted by chiral models: $\text{Re} V_{opt} = -60\rho/\rho_0$ MeV [3, 4, 5, 6, 7]; $\text{Im} V_{opt} \approx -60\rho/\rho_0$ MeV, as in the experimental paper [1] and the theoretical study of [4].

In the Monte Carlo simulation [26] we implement this distribution by generating a random kaon mass $\tilde{M}_K$ around a central value, $M_K + \text{Re} V_{opt}$, within a certain extension determined by the width of the distribution $\Gamma_K = -2\text{Im} V_{opt}$. The probability assigned to each value of $\tilde{M}_K$ follows the Breit-Wigner distribution given by the kaon spectral function:

$$S(\tilde{M}_K) = \frac{1}{\pi} \frac{-2M_K \text{Im} V_{opt}}{(\tilde{M}_K^2 - M_K^2 - 2M_K \text{Re} V_{opt})^2 + (2M_K \text{Im} V_{opt})^2} \,.$$

In Fig. 1 we show the results of the Monte Carlo simulation obtained with an optical potential $V_{opt} = (-60, -60)\rho/\rho_0$ MeV [26]: first, taking into account only quasi-elastic processes; and then taking into account all the discussed mechanisms. We can see that there is some strength gained in the region of "bound kaons" due to the new mechanisms. Although not shown separately in the figure, we have observed that one nucleon absorption and several rescatterings contribute to the region $-E_B > -50$ MeV. To some extent, this strength can be simulated by the parametric background used in [1]. However, this is not true anymore for the two nucleon absorption process, which contributes to all values of $-E_B$, starting from almost as low as -300 MeV.

It is very important to keep in mind that in the spectrum of [1] the outgoing forward protons were measured in coincidence with at least one charged particle in the decay counters sandwiching the target. Obviously, the real simulation of such a coincidence experiment is tremendously difficult, practically impossible with high accuracy, because it would require tracing out all the charged particles coming out from all possible scatterings and decays. Although we are studying many processes and following many particles in our Monte Carlo simulation, which is not the case in the Green function method used in the data analysis [1], we cannot simulate precisely the real coincidence effect.
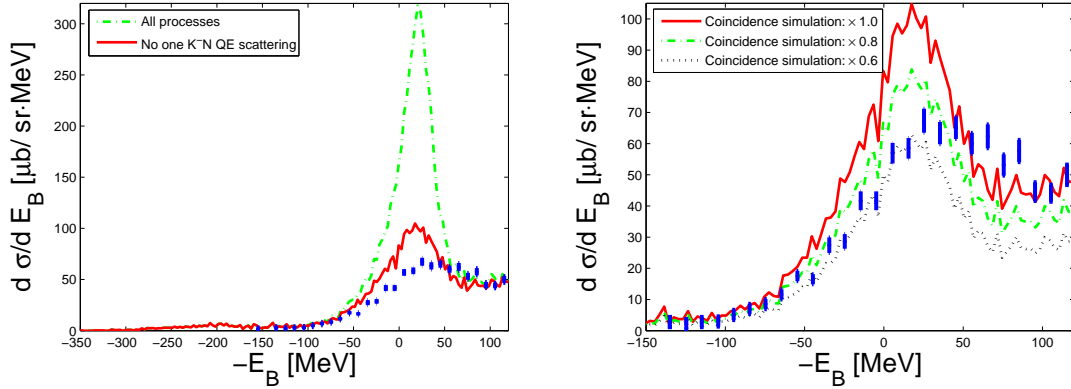
FIGURE 2. Calculated $^{12}C(K^-, p)$ spectra with $V_{opt} = (-60, -60)\rho/\rho_0$ MeV to be compared with data points from [1]. *Left plot:* Dash-dotted line shows the spectra calculated taking into account all contributing processes; then imposing minimal coincidence requirement we obtain spectra shown by a full line. *Right plot:* Solid line shows spectra with minimal coincidence requirement, as on the left plot; dash-dotted and dotted lines - the same spectra with additional suppression factors - dash-dotted and dotted lines.

The best we can do is to eliminate the processes which, for sure, will not produce a coincidence; this can be called minimal coincidence requirement [26]. If the kaon in the first quasi-elastic scattering produces an energetic proton falling into the peaked region of the spectra, then the emerging kaon will be scattered backwards. In our Monte Carlo simulations we can select events were neither the proton, nor the kaon will have any further reaction after such a scattering. In these cases, although there is a "good" outgoing proton, there are no charged particles going out with the right angle with respect to the beam axis to hit a decay counter, since the K^- escapes undetected in the backward direction. Therefore, this type of events must be eliminated for comparison with the experimental spectra.

It is clear from Fig. 1 that the main source of the energetic protons for $^{12}C(K^-, p)$ spectra is K^-p quasi-elastic scattering, however many of these events will not pass the coincidence condition. Implementing the minimal coincidence requirement, as discussed above, we will cut off a substantial part of the potentially "good" events, and drastically change the form of the final spectrum [26], as illustrated in Fig. 2, left plot.

To further simulate the coincidence requirement we introduce additional constant suppression factors to the obtained spectrum - see Fig. 2, right plot. Comparing our results with the experimental data we can conclude that in the "bound" region, $-E_B < 0$ MeV, this additional suppression is about ~ 0.7 and more or less homogeneous, while in the continuum the suppression weakens and for $-E_B > 50$ MeV it is negligible. This picture is natural from the physical point of view, because the r.h.s. of the spectrum, Fig. 2, with relatively low momentum protons is mostly populated by many particle final states, which have a good chance to score the coincidence.

To conclude, the main point of our analysis is not to state that the data of Ref. [1] supports $\text{Re} V_{opt} = -60\rho/\rho_0$ MeV rather than $-200\rho/\rho_0$. We want to make it clear that trying to simulate these data one necessarily introduces large uncertainties due to the

experimental set up. Thus, this experiment is not appropriate for extracting information on the kaon optical potential [26].

Contrary to what it is assumed in Ref. [1], we clearly see, Fig. 2, that the spectrum shape is affected by the required coincidence. The experimental data without the coincidence requirement would be a more useful observable.

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